NASA TECHNICAL MEMORANDUM

NASA TM X-73473

NASA TM X-73473

(NASA-TM-X-73473) ADVANCED COMBUSTION TECHNIQUES FOR CONTROLLING NO SUB x EMISSIONS OF HIGH ALTITUDE CRUISE AIRCRAFT (NASA) 21 p HC A02/MF A01 CSCL 21E

N77-10062

Unclas

G3/07 08913

ADVANCED COMBUSTION TECHNIQUES FOR CONTROLLING NO_X EMISSIONS OF HIGH ALTITUDE CRUISE AIRCRAFT

by R. A. Rudey and G. M. Reck
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER to be presented at
Twenty-seventh International Astronautical Congress
sponsored by the American Institute of Aeronautics and Astronautics
Anaheim, California, October 10-16, 1976

27TH INTERNATIONAL ASTRONAUTICAL CONGRESS
ANAHEIM, CALIFORNIA, USA
OCTOBER 10-17, 1976

ADVANCED COMBUSTION TECHNIQUES FOR CONTROLLING NO_x EMISSIONS OF HIGH ALTITUDE CRUISE AIRCRAFT

R. A. Rudey and G. M. Reck
NASA Lewis Research Center
Cleveland, Ohio

Abstract

An array of experiments have been and continue to be sponsored and conducted by NASA to explore the potential of advanced combustion techniques for controlling the emissions of aircraft into the upper atmosphere. Of particular concern are the oxides of nitrogen (NO_x) emissions into the stratosphere. The experiments utilize a wide variety of approaches varying from advanced combustor concepts to fundamental flame tube experiments. Results are presented which indicate that substantial reductions in cruise NO_x emissions should be achievable in future aircraft engines. A major NASA program is described which focuses the many fundamental experiments into a planned evolution and demonstration of the prevaporized-premixed combustion technique in a full-scale engine.

E-8855

I. Introduction

This paper describes those activities currently underway at the U.S. National Aeronautics and Space Administration (NASA) that are specifically aimed at reducing the cruise oxides of nitrogen (NO_x) emissions of high altitude aircraft.

Two recent U.S. studies regarding the potential adverse impact of aircraft exhaust emissions on the upper atmosphere (stratosphere) have concluded that the NO_x and oxides of sulfur (SO_x) emitted by future fleets of high altitude cruise aircraft could influence the stratospheric ozone concentration and the earth's albedo, references 1 and 2. Both studies recommended that major reductions in both NO_x and SO_x be sought in future gas turbine engines for both subsonic and supersonic aircraft. The recommended SO_x levels can be achieved by removing the sulfur contained in the aircraft's fuel. However, the recommended NO_x emission reductions from current levels (minimum by a factor of six to a maximum by a factor of 100) will require major modifications to conventional engine combustion systems. NASA is promoting, conducting and sponsoring projects that are aimed at evaluating the combustion techniques needed to achieve these reductions and to evolve, if possible, attractive NO_x emission reduction techniques into practical engine combustors. These projects encompass a range of technology ranging from minor modifications to existing conventional engine combustors to fundamental flame tube type studies. The final goal of these efforts is to reduce cruise NO_x emissions to the lowest possible level while still maintaining acceptable performance in terms of fuel consumption, durability, maintainability, and safety. In addition to the above constraints, any viable combustion system must be also capable of meeting local environmental standards, such as the U.S. Environmental Protection Agency (EPA) aircraft emission standards, reference 3. Therefore, emissions at idle, climbout, and takeoff must also be controlled.

This paper presents and discusses some of the results obtained from research and development programs being sponsored, directed, and/or conducted by NASA. Although we recognize that much important work is being conducted at or sponsored by universities, private industry and other government agencies (DOD, FAA, EPA, etc.), this paper will concentrate on NASA programs only. An array of activities ranging from investigating variations to conventional combustion systems on through to evaluating advanced catalytic techniques are being pursued. Application of these techniques to future aircraft engines are being considered and both subsonic and supersonic flight regimes are of concern. The results pertinent to the NO_x emission reduction efforts are presented and discussed along with an assessment of the projected development difficulties and a forecast of potential emission level reductions. A recently implemented NASA effort called the Stratospheric Cruise Emission Reduction Program (SCERP) is also described and discussed.

II. NO_x Emission Control Techniques

The largest single factor which controls the formation of NO_x in a combustion process is the flame temperature in the reaction zone. An example of this effect is illustrated in figure 1 where NO_x concentration is plotted as a function of flame temperature. The values shown were calculated using a well-stirred reactor model and are representative of the levels generated in a completely homogeneous prevaporized-premixed combustion process with a 2 millisecond residence time, τ (typical of contemporary engine combustors).

Because of the exponential variation of NO_x formation as a function of flame temperature, controlling flame temperature in a combustion process should provide a very powerful tool for controlling NO_x emissions. Combustion scientists and engineers are pursuing and evaluating techniques to achieve flame temperature reductions using the so-called "lean combustion" approach. Lean combustion in the present vernacular is normally associated with equivalence ratios (ratio of local to stoichiometric fuel/air ratio), ϕ, between 0.4 and 1. NASA's aircraft gas turbine engine NO_x emission reduction efforts are primarily aimed toward exploring the potential of this lean combustion approach for eventual application to practical engine combustors.

Lean Combustion Experiments

Conventional combustion. - Experimentation aimed at exploring the potential reductions that could be expected by modifying conventional combustors has concentrated on trying to "lean-out" the primary zone, as illustrated in figure 2 and described in

reference 4. Results from the reference 4 study are illustrated on figure 3 where NO_x emission index is plotted as a function of a calculated primary-zone equivalence ratio, ϕ_p, and overall combustor equivalence ratio ϕ_o. At a constant overall ϕ_o of 0.21, NO_x emissions were reduced approximately 30 percent by reducing ϕ_p from 0.74 to 0.34. This level of reduction is many times smaller than what could be accomplished in a homogeneous prevaporized-premixed combustion process as illustrated in figure 1. The reason for this "shortfall" in NO_x emission reduction with reduced ϕ_p is due to the inability to avoid droplet burning (ϕ=stoichiometric) in the primary-zone and the likelihood that the actual ϕ_p was not as lean as the computed ϕ_p (due to nonhomogeneities in the primary-zone). Thus local "rich" combustion regions produced large amounts of NO_x. Similar results have also been obtained in NASA's Experimental Clean Combustor Program (contract effort with General Electric and Pratt & Whitney), references 5 and 6, wherein a variety of modifications were evaluated. Examples of several of these modifications will be described in a latter section of this paper. All in all it would appear the NO_x reductions of up to 50 percent may be achievable in conventional type combustors by employing lean combustion in the primary-zone and by appropriate control of residence time. It also appears that these reductions can be achieved along with acceptable combustor performance requirements as indicated in references 5 and 6.

Forced-circulation technique. - The term "forced-circulation" is used to describe the use of strong swirling flow or impinging jets to form a powerful recirculation cell or cells in a combustor primary-zone. The powerful recirculation cell provides a mechanism for entraining hot combustion gases into the flame region thereby establishing a stable zone for lean combustion to occur. When these recirculation cells are coupled with a partially prevaporized-premixed fuel-air mixture, as is illustrated in figure 4, the combustion process can begin to approach the homogeneous process more closely than any modification to the conventional combustion technique. The two concepts shown on figure 4, Jet-Induced-Circulation (JIC) and Vortex-Airblast (VAB), are being evaluated under NASA contract to the SOLAR Division of International Harvestor Company. To date these concepts have been and continue to be evaluated in a tubular configuration but a full annular model is planned for the future. References 7 and 8 give details of these experiments and a representative plot of the "best" emission results obtained is shown in figure 5. The VAB concept achieved a NO_x emission index of approximately 1 g NO_2/Kg fuel at the designated simulated supersonic cruise operating design point (inlet pressure was not a true simulation). The JIC concept was capable of producing a NO_x emission index of 2 g NO_2/Kg fuel. Both of these values represent substantial reductions (approximately a factor of 10) from conventional combustor emissions at similar operating conditions. Both concepts were optimized for "lean" combustion at the design point (designated cruise conditions) hence low temperature rise performance was characterized by instability and low efficiency. Design point efficiency was in excess of 99.5 percent. Currently, the ability of these concepts to satisfy off-design (idle through takeoff) operating requirements is being evaluated.

Prevaporized-premixed technique. - Perhaps the most successful method of reducing NO_x emissions to extremely low levels has been the completely prevaporized-premixed combustion technique. Studies of this technique have been investigated by a large cross-section of the combustion technical community. In most instances, the studies are conducted in experimental "flame-tubes" such as the two illustrated on figure 6. Both flame-tubes employ a vaporizer-mixer section, a flame holder (cone for the General Applied Physics Laboratory (GASL) apparatus and a perforated plate for the NASA apparatus), a flame zone, and a gas sample extraction probe. The NASA apparatus has both liquid and vapor fuel capability. Application of the completely prevaporized-premixed technique to actual combustors has been suggested but no "combustor-like" hardware has been investigated by NASA.

The results of some of the NASA and GASL experiments (sponsored by NASA) are summarized in figures 7 and 8. Details regarding these experiments are given in references 9 and 10. Values of NO_x emission index below 0.5 g NO_2/Kg fuel were achieved in both of the experiments and close agreement between the results of the two experiments was realized. From figure 7 one can see that if combustion efficiency is to be maintained above 99.5 percent (a likely requirement for cruise performance), the NO_x emission index would have to be 0.4 g NO_2/Kg fuel or higher. The principal factor which controls efficiency of the prevaporized-premixed combustion process is residence time as shown on figure 8. If one allows residence time to increase (either by reducing flow velocity or making the combustor larger) high values of efficiency can be obtained at the very low equivalence ratios needed for obtaining extremely low values of NO_x emissions. Therefore, it would appear that values below 0.5 g NO_2/Kg could be obtained if one could independently control residence time. In evaluating the values of emission index obtained in these experiments and as displayed in figures 7 and 8, considerable care should be taken. These were carefully controlled experiments, wherein all parameters such as air and fuel flow, pressure, and temperature were maintained very stable, which did not necessarily represent the type of environment that would be present within a normal gas turbine engine. Also they essentially represent near design point type of operation (particularly inlet temperature) where conditions are favorable for effective fuel vaporization and lean combustion stability. Nevertheless, the results do indicate that the prevaporized-premixed combustion technique is a strong candidate for reducing aircraft NO_x emissions to extremely low values and certainly warrants continued investigation.

Catalytic Combustion Experiments

Perhaps one of the most unique concepts for reducing aircraft gas turbine emissions is the potential application of catalyst elements to enhance the reaction process of extremely lean fuel-air mixtures. For exploring the potential of this concept, NASA is employing the apparatus shown schematically in figure 9 and described in detail in reference 11. The apparatus consists of a vaporizer-mixer section, a catalyst element section, and a probe for extracting a gas sample for analysis. The schematic illustration shows that up to four catalyst

elements can be used in a typical test. All four elements can be varied in terms of the catalyst type and the substrate structure. This allows for an optimization of pressure drop and temperature rise across the entire catalyst bed. Extremely low NO_x emissions (below measurable quantities) have been obtained in experiments when using propane fuel premixed with air. Propane was used to insure complete vaporization prior to contact with the catalyst elements. Several of the problems of using this concept are the inherent narrow efficient operating range (dramatic efficiency losses occur at very low off-design equivalence ratios), limited high temperature capability due to catalyst and substrate melting, potential catalyst poisoning by fuel impurities, and the need to preheat the bed or fuel-air mixture to initiate reactions (cold start not possible). Nevertheless, the potential of the catalyst concept will continue to be explored both as a total combustion system and for possible use as a lean stability augmentation device for application to a hybrid catalyst-prevaporized-premixed type combustion system.

Off-Design Considerations

Up to this point all of the discussion has centered about results obtained at selected design points simulating supersonic cruise conditions. Optimization for low NO_x emissions at this condition required the use of lean burning which for a primary-zone ϕ of less than 0.5 uses much of the available air in the combustion process. This type of airflow distribution presents a problem when the combustor most be operated at the low overall equivalence ratios that are required for engine idle. Poor stability and poor efficiency generally are the result. The SOLAR VAB concept was reconfigured to optimize the primary zone ϕ for the idle condition in order to improve stability and to minimize the formation of idle pollutants such as carbon monoxide (CO). The effect of this change on both the idle and cruise point emissions is shown on figure 10. As the fuel flow was increased to obtain the required cruise temperature rise, the primary-zone ϕ actually went through stoichiometric and into a rich burning condition. The result was unacceptably high levels of NO_x and CO emissions.

These results clearly indicate the need for either some form of staged combustion or variable control that can maintain primary zone ϕ at the optimum level needed to satisfy both engine demands and emission level requirements. A significant effort to evaluate the potential of the staged combustion approach, using conventional combustion techniques, has been and continues to be explored in the NASA Experimental Clean Combustor Program, references 5 and 6. NASA plans to explore the potential of the variable geometry approach in the Stratospheric Cruise Emission Reduction Program that is described later in this paper. Regardless of which technique proves to be the most desirable and practical, the impact of off-design performance and emission requirements must be considered when evaluating the level of potential gains that may be achieved by employing the advanced combustion techniques currently being investigated. Many compromises are certainly going to be required in order to evolve practical, operational combustors for future aircraft engines.

III. Application of Emission Control Techniques

Since future supersonic cruise aircraft may employ variable cycle engines with possible thrust augmentation, the potential application of the NO_x emission control techniques must be evaluated in terms of both primary combustors and thrust augmentors (especially duct burners). In response to the need for evaluating the problems involved in these applications, NASA is currently conducting studies to apply conventional low NO_x combustion techniques to contemporary engine primary burners and to experimental duct burners. Two of these efforts are described below. No comparable effort has been undertaken to evaluate the application difficulties expected for the forced-circulation, prevaporized-premixed, or the catalytic techniques at the present time although plans to do so in the future are being formulated and will be described in a later section of this paper.

Main Burners

The principal effort to apply the lean burning conventional technique to primary burners of current subsonic and possible future supersonic cruise aircraft engines has been conducted in the Experimental Clean Combustor Program. In all cases, the desired application required the use of the staged combustion approach wherein one stage (pilot) was optimized for acceptable idle/taxi emissions and performance and one stage (main) for the high power takeoff emissions and performance. Several examples of staged concepts are illustrated in figure 11. Figures 11a and 11b represent cross-sections of full annular adaptations of a two-row swirl-can-modular concept and a double-annular concept to a General Electric CF6-50 engine and figure 11c a vorbix concept for a Pratt & Whitney JT9D-7 engine. Although these concepts were designed for specific subsonic engines, they were also modified in an attempt to optimize their NO_x emission performance at simulated supersonic cruise conditions (references 5 and 6). By proper scheduling of both fuel and air flow between the two stages, reductions in NO_x emissions of approximately 50 percent were achieved at both the selected subsonic and supersonic cruise conditions as compared to present in-service engines at comparable operating conditions. Some of the principal development activities still needed to make these two-stage combustors acceptable for operational engine adaptation include defining and optimizing the staging characteristics during acceleration, deceleration and part power operation, and defining accurate control parameters and control functions to permit smooth staging to occur. A considerable amount of information regarding these staging characteristics as well as emission performance will be generated during the full scale engine tests of the double annular in the CF6-50 and the vorbix in the JT9D-7 that are scheduled during the latter part of 1976.

Duct Burners

NASA currently is sponsoring two activities that are aimed at defining the expected emission levels that can be obtained by applying NO_x emission control techniques to candidate duct burners for possible supersonic cruise aircraft engines. Both efforts, an experimental study by General Electric

and an analytical study by Pratt & Whitney are being conducted under contract with NASA. The analytical study at Pratt & Whitney will eventually be expanded into an experimental study of several attractive concepts. A schematic illustration of one configuration of a staged-combustion concept currently under evaluation at General Electric is shown in figure 12. As with the main burners, one stage (pilot) is optimized to provide low CO and unburned hydrocarbon (THC) emissions at low power and the other stage (main) low NO_x at high power. The configuration shown is a variation of a radial/axial staged primary combustor that was evaluated in reference 5. The NO_x emission level goal for the duct burner application is 1 g NO_2/Kg fuel at the designated supersonic cruise condition with a 99 percent or higher combustion efficiency. Further considerations include the necessity to meet proposed local emission standards currently under study by the U.S. EPA and performance requirements during transonic acceleration (most severe temperature rise condition). These multiple requirements when coupled with operational considerations, such as "soft" light-off, led to the need for a staged-combustion concept. Experimental testing has just recently begun.

IV. Assessment of Results

The NO_x emission reduction potential of the various control techniques for future engines was estimated by utilizing projected engine cycle conditions and accepted extrapolation/correlation methods. Although extrapolation/correlation methods are constantly being updated as experimental results are obtained, the results of the previously described activities were extrapolated to the projected cycle conditions using the following equation(1):

$$(EI)_2 = (EI)_1 \left[\frac{(P_3)_2}{(P_3)_1}\right]^{-0.5} \exp\left[\frac{(T_3)_2 - (T_3)_1}{288}\right]\left[\frac{(T_4)_2}{(T_4)_1}\right]$$

where: EI - emission index
P_3 - combustor inlet pressure
T_3 - combustor inlet temperature
T_4 - combustor outlet temperature
1 - experimental test conditions
2 - designated operating conditions

Projected Engine Cycles

The projected subsonic and supersonic cruise engine cycle parameters that are needed as inputs to equation (1) are presented in Table I.

For the subsonic high altitude cruise case, the current operating conditions of both the Pratt & Whitney JT9D-7 and the General Electric CF6-50 engines are shown. These conditions were selected because they encompass an engine cycle pressure ratio range from approximately 22:1 to 30:1. It is conceivable that higher pressure ratios will be used in future energy conservative engines but, at the present time, the above pressure ratio range is felt to be representative for most of the high altitude, long range subsonic cruise aircraft that are expected to be in service during the next several decades. A Mach 0.85 cruise speed at an average altitude of 10.7 kilometers was used to compute the engine cycle parameters.

For the supersonic cruise case, the operating conditions of two advanced study engines were used. The two engine cycles, one by Pratt & Whitney and one by General Electric, represent current values from a NASA sponsored study to evaluate potentially attractive propulsion systems for possible future supersonic cruise aircraft. The cycle parameters encompass an engine cycle pressure ratio range of approximately 20:1 to 25:1. A Mach 2.32 cruise speed at an average altitude of 16 kilometers was used to compute the engine cycle parameters. Since the NASA sponsored study is not yet complete, the final values for the cycle parameters of the two study engines could vary somewhat from those shown in Table I. However, for the purpose of estimating the NO_x emissions for future supersonic cruise aircraft engines, the values shown should be reasonably representative.

Emission Level Forecast

Using the engine cycle cruise parameters shown in Table I, emission level forecasts were made for the various NO_x control techniques previously described. The emission level forecasts are presented and compared to levels that could be expected from conventional technology combustors (current CF6 and JT9D types) operating at the same conditions in figures 13 and 14. All of the values shown on these figures represent extrapolations from either rig test or engine test conditions to the designated cruise conditions by using equation (1). They also represent NO_x emission levels at combustion efficiencies in excess of 99.5 percent.

The application of the "clean combustor technology" would provide a potential reduction in projected subsonic cruise NO_x emissions of about a factor of 2 to 3. To achieve reductions by a factor of 6 or more (recommendation of reference 1) the implementation of either the "forced-circulation," prevaporized-premixed or catalytic combustion techniques will be required. Of these latter three techniques, the "forced-circulation" technology is further along in the process of converting fundamentals to combustor hardware but also offers the least gains. Based on the extrapolations, only the prevaporized-premixed and catalytic techniques offer the potential for reducing emissions below 1 g NO_2/Kg fuel at the designated subsonic cruise conditions.

The actual achievable levels may be somewhat different (probably higher) when these emission control techniques are developed into operational engine hardware. Trade-offs between emissions, performance, altitude relight, durability, maintainability and complexity as well as the influence of the actual engine environment versus the carefully controlled rig experiments will have to be considered. The end result will likely be some upward adjustment to the levels shown on figure 13. Actual engine demonstration and technology development must be conducted before the levels can be quantified and considered to accurately represent achievable levels. However, the general trends displayed by employing the various techniques should be reasonable.

The projected supersonic cruise condition emission levels for the various NO_x control techniques are shown on figure 14. As in the subsonic case, the level of potential reduction is greater with the

lesser developed techniques. The projected supersonic cruise values are approximately a factor of two higher than subsonic cruise values because the combustor inlet and outlet conditions are more severe from a NO_x formation standpoint as illustrated by the cycle conditions given in Table I. As in the subsonic case, trade-offs will most certainly effect the absolute values and engine demonstrations will be needed prior to quantifying the achievable levels. Because of the severe conditions (high cycle pressure ratio), the projected emissions of the conventional technology combustors are significantly higher than current SST engines (≈20 g NO_2/Kg fuel). Employing "clean combustor technology" would result in reducing the NO_x emissions to levels nearly equal to present day SST's. To achieve reductions of a factor of 6 or more from present levels will definitely require the application of prevaporized-premixed or catalytic techniques.

In evaluating these results, please bear in mind that the levels were extrapolated to the designated conditions by using equation (1). In some of the fundamental investigations (e.g. prevaporized-premixed), the effect of combustor inlet pressure and temperature resulted in some anomalies from the relationships described by equation (1). These anomalies could have an impact on the final extrapolated levels and will be discussed later. The trends however are clear. The low levels of cruise NO_x emissions recommended by references 1 and 2 will most likely require the development and implementation of the less developed, higher risk technology associated with the prevaporized-premixed and catalytic techniques.

Estimated Application Difficulty

A qualitative assessment of the ability of each technique to control cruise NO_x emissions and the difficulty of successfully applying these techniques to operational aircraft engines was made and is summarized in Table II. As shown, and previously noted, either staged or variable geometry combustion approaches will be needed to satisfy engine operational requirements. For each application a relative degree of difficulty is estimated. From a comparative standpoint, the coupling of conventional techniques within a staged combustor would represent the "lowest" development risk of the techniques considered. The term "development risk" is defined as the estimated degree of difficulty required to convert a demonstrated experimental technique into a production combustor for an advanced aircraft gas turbine engine.

In addition to the emission control and performance factors involved in assessing the potential for applying the emission reduction techniques that were evaluated, many other factors must also be considered. Some of the principal factors would include: increases in complexity of the staged and variable geometry designs; engine acceleration and deceleration characteristics; the effect of engine imposed variations in flow, temperature and pressure; and the development of adequate fuel controls. Full-scale engine tests are needed to evaluate the impact of these factors.

V. Stratospheric Cruise Emission Reduction Program

In response to the need for substantial cruise NO_x emission reductions, highlighted by the studies mentioned earlier (Refs. 1 and 2), NASA has initiated the Stratospheric Cruise Emission Reduction Program (SCERP). The SCERP objective is to develop and demonstrate the technology necessary to reduce cruise NO_x emissions by a factor of 6 or more from current levels and to meet the current EPA 1979 emission standards for the airport vicinity. The activity will be targeted for the high bypass ratio, high pressure ratio engines currently powering the wide-body subsonic transports. Technology evolved by SCERP, although not directly applicable, should also aid in the development of low NO_x combustors for future supersonic cruise aircraft engines.

The prevaporized-premixed technique for emission reduction will be explored in the SCERP activity. The results shown earlier in figure 7 indicate that this technique has the potential to meet or exceed the program goal. While this technique does not offer the emission reduction potential of the catalytic approach, the practical problems associated with its application are viewed as less severe. However, from the earlier discussion of off-design considerations it is apparent that a form of variable geometry will likely be necessary to maintain acceptable combustor performance as well as low emissions over the entire flight envelope. In addition, it is expected that an advanced digital control system will likely be required for the eventual engine application.

The program plan for SCERP, shown in figure 15 is broken into four successive phases leading to an engine demonstration. Phase I will consist of a number of fundamental studies to establish design criteria for prevaporized-premixed combustors eventually leading to the development and assessment of a number of combustor concepts. In Phase II, a number of variations of each concept will be experimentally screened to identify the most promising. These designs will then be further developed in Phase III to optimize off-design performance, ignition, liner cooling, altitude relight, etc. The best design will be selected for full-scale engine demonstration in Phase IV.

An important consideration at the end of the first phase concerns the potential of the various designs for application in existing engines. If a determination is made that the concept required to achieve the emission level goals can be adapted to an existing engine with reasonable modifications, then a target engine will be selected and the remaining phases of the program will be directed toward demonstration of the concept in that engine. This approach is identified as the "constrained" path in figure 15. If, however, a conclusion is reached that the required concept cannot be adapted to an existing engine, then the subsequent program will follow the "unconstrained" path. In this approach the candidate concept will be screened and developed to optimize emissions performance and the best combustors will be used to define the characteristics of a compatible engine.

The Phase I activities will be most critical to program success. A number of fundamental studies are being initiated to examine four key problem areas associated with the practical application of the prevaporized-premixed combustion technique. These areas are identified in Table III along with

their constituent activities.

Several of the lean combustion study elements listed in Table III are extensions of flame-tube investigations underway at NASA. A study of the effect of fuel preparation on emissions will be conducted to examine the influence of the degree of vaporization, mean dropsize, and other spray characteristics. Figure 16 shows emissions data taken from the GASL experiment described in reference 10. NO_x emission index is plotted as a function of pressure for several lean equivalence ratios. The expected dependency on the square root of pressure is not observed, and emission minima occur near 8 atmospheres. This effect is likely associated with the prevaporizing-premixing process and may result from an improvement in vaporization rate at the higher pressure conditions. A similar pressure effect was observed with the VAB combustor described earlier, but not with the JIC combustor, indicating the need for a more thorough understanding of the effects of fuel preparation on emission.

Another lean combustion experimental study will parametrically examine the effects of engine cycle parameters on emissions. Emissions measurements of a premixed propane combustor will be made over a wide range of conditions up to 30 atmospheres and 1000 K. The effect of simple flameholder geometries on emissions and combustor performance will be investigated in a third study, while a fourth activity will examine several schemes for improving lean stability limits.

In the area of fuel preparation, engine measurements are being made to characterize the compressor discharge turbulence. The nature of the turbulence in the diffuser inlet may promote fuel mixing and vaporization if fuel is introduced in this region. In addition, techniques for vaporizing fuel external to the combustor will be studied and schemes for controlling radial fuel-air distribution will be examined.

Autoignition and flashback present serious hazards to potential prevaporizing-premixing combustors. Many of the flame-tube studies including both GASL and NASA have experienced autoignition or flashback at some conditions. Figure 17 illustrates the autoignition problem. The vaporization times shown in the figure were derived from a simplified program developed at NASA and the ignition delay values were obtained from reference 12. It is apparent that at higher cycle pressure ratios if the fuel is given sufficient time to completely vaporize, it may autoignite. The SCERP studies in this area will begin with a parametric study of the factors influencing autoignition delay up to pressures in excess of 25 atm. The effect of hot surfaces on autoignition will be studied as will the effects of boundary layers and engine transients on flashback.

The fourth area, identified as engine constraints refers to problems arising from the interfaces between the combustor and the engine. The characteristics of the compressor discharge airflow are of particular concern in a premixing combustor to assure control of the homogeneity of the fuel-air mixture. In addition to the turbulence measurements mentioned previously, an investigation of the circumferential airflow uniformity at the compressor exit will be conducted. Another study will examine the effects of nonideal turbine inlet temperature profiles on turbine life and performance. With an extremely lean primary zone, considerably less dilution air may be available for tailoring the combustor exit temperature profile. As part of a third effort, a simplified combustor model will be incorporated into an engine transient performance computer routine to investigate the interaction of the combustor with the remainder of the engine during acceleration and deceleration. With variable geometry, transient performance may be a serious concern.

As the results of the Phase I studies become available, the design data will be applied to combustor concepts. Variable geometry techniques and controls will be incorporated into the designs as required. As the designs evolve, an assessment of their potential with regard to both emissions reduction and practical application will be made. The most promising concepts will then be selected for experimental screening.

VI. Concluding Remarks

Results obtained from a variety of projects, varying in degree of technological advancement currently being conducted and sponsored by NASA indicate that substantial reductions in cruise NO_x emissions should be achievable in future subsonic and supersonic aircraft gas turbine engines. The degree of reduction achievable is, of course, dependent upon the level of advanced combustion technology that is judged to be developable into operational combustors. At designated cruise design points, advanced combustor technology of the type currently being evaluated in the NASA Experimental Clean Combustor Program offers the promise of reducing NO_x emissions by about a factor of 2 from current engine levels. Reductions beyond these levels will require the application of higher risk technology such as prevaporized-premixed combustion concepts. Results from controlled experiments indicate that this more advanced technology may provide reductions of a factor of 6 or greater from current levels. It is important to note that these reductions have only been achieved in controlled "rig type" experiments and they must certainly be quantified in full-scale engines. Since control of emissions at all operating conditions, from idle/taxi on up to cruise, will be required in future engines, some form of combustion staging or variable geometry will be needed regardless of the level of advanced technology employed. This added complexity will likely effect the final achievable levels of cruise NO_x and will also increase the development risk involved. Much additional information is still needed before the impact of off-design conditions can be quantified.

Continuing U.S. studies aimed at defining the probable engine cycle conditions for future supersonic cruise vehicles indicate that cycle pressure ratios are likely to be higher than those previously used for estimating future engine emissions. These higher cycle pressure ratios have a direct impact on the NO_x emission levels that can be forecasted based on the present experimental results. Values considerably higher than previous estimates are projected when conventional correlating parameters are applied. Recent parametric tests of the full and partial prevaporized-premixed techniques,

however, revealed some anomalies with regard to the pressure and temperature effect on NO_x formation. Much more information on these effects must be obtained before reasonably accurate extrapolations can be made.

The message then would seem to be clear. A careful, systematic approach is needed to answer the anomalies, to fill in the gaps in fundamental knowledge, such as autoignition and flashback, to determine the trade-offs between complexity and emission reduction potential, and to finally demonstrate the performance of the high risk, low NO_x emission technology in an actual engine environment. The goals and approach of the NASA Stratospheric Cruise Emission Reduction Program (SCERP) have been structured to satisfy most of these needs. Because of the NO_x emission reduction promise that the high risk technology has indicated in controlled experiments, programs such as SCERP are needed to provide the data bank required to properly assess the ability to convert this technology into practical engine combustors. This then will help determine the ability of future high altitude cruise aircraft engines to meet the levels recommended by environmental studies.

VII. References

1. A. J. Grobecker, S. C. Coroniti, and R. H. Cannon, Jr., "The Effects of Stratospheric Pollution by Aircraft, Report of Findings," Department of Transportation Rept. TST-75-50, 1974.
2. "Environmental Impact of Stratospheric Flight," National Academy of Sciences, 1975.
3. "Control of Air Pollution for Aircraft Engines - Emission Standards and Test Procedures for Aircraft," Federal Register, Vol. 38, No. 136, pp. 19087-19103, July 17, 1973.
4. C. J. Norgren and R. D. Ingebo, "Effect of Primary-Zone Equivalence Ratio and Hydrogen Addition on Exhaust Emissions in a Hydrocarbon-Fueled Combustor," National Aeronautics and Space Administration, TM X-3177, 1974.
5. D. W. Bahr and C. C. Gleason, "Experimental Clean Combustor Program, Phase I Final Report," National Aeronautics and Space Administration CR-134737, GE74AEG380, 1975.
6. R. Roberts, A. Peduzzi, and G. E. Vitti, "Experimental Clean Combustor Program, Phase I Final Report," National Aeronautics and Space Administration CR-134736, PWA-5153, 1975.
7. P. B. Roberts, D. J. White, and J. R. Shekleton, "Advanced Low NO_x Combustors for Supersonic High-Altitude Aircraft Gas Turbines," National Aeronautics and Space Administration CR-134889, RDR-1814, 1975.
8. P. B. Roberts, J. R. Shekleton, D. J. White, and H. F. Butze, "Advanced Low NO_x Combustors for Supersonic High-Altitude Aircraft Gas Turbines, ASME Paper 76-GT-12, March 1976.
9. D. Anderson, "Effects of Equivalence Ratio and Dwell Time on Exhaust Emissions from an Experimental Premixing, Prevaporizing Burner." ASME Paper 75-GT-69, March 1975.
10. G. Roffe and A. Ferri, "Prevaporization and Premixing to Obtain Low Oxides of Nitrogen in Gas Turbine Combustors," National Aeronautics and Space Administration CR-2495, 1975.
11. D. Anderson, "Preliminary Results from Screening Tests of Commercial Catalysts with Potential Use in Gas Turbine Combustors Part II - Combustion Test Rig Evaluation." National Aeronautics and Space Administration, TM X-73412, 1976.
12. L. J. Spadaccini, "Autoignition Characteristics of Hydrocarbon Fuels at Elevated Temperatures and Pressures," ASME Paper 76-GT-3, March 1976.

TABLE I. - ENGINE CYCLE CRUISE PARAMETERS

ENGINE	COMBUSTOR INLET PRESSURE, ATM	COMBUSTOR INLET TEMPERATURE, K	COMBUSTOR EXIT TEMPERATURE, K
CF6-50[a]	11.4	733	1449
JT9D-7[a]	9.3	704	1413
GENERAL ELECTRIC DOUBLE BYPASS[b]	9.4	887	1809
PRATT & WHITNEY VARIABLE STREAM CONTROL[b]	14.1	985	1755

[a]MACH 0.85, 10.7 KM ALTITUDE.
[b]MACH 2.32, 16 KM ALTITUDE.

TABLE II. - QUALITATIVE COMPARISON OF ESTIMATED EMISSION REDUCTION POTENTIAL AND APPLICATION DIFFICULTY FOR SELECTED NO_x EMISSION REDUCTION TECHNIQUES

EMISSION REDUCTION TECHNIQUE	NO_x EMISSION REDUCTION POTENTIAL	ENGINE APPLICATION DIFFICULTY	
		STAGED	VARIABLE GEOMETRY
CONVENTIONAL			
(a) LEAN BURNING	MODERATE	MAJOR MODIFICATION *(HIGH DEVELOPMENT RISK)	MAJOR MODIFICATION (VERY HIGH DEVELOPMENT RISK)
(b) QUICK QUENCHING	MODERATE	SAME AS (a)	SAME AS (a)
PREVAPORIZED/PREMIXED	VERY GOOD	VERY MAJOR MODIFICATION (VERY HIGH DEVELOPMENT RISK)	VERY MAJOR MODIFICATION (VERY HIGH DEVELOPMENT RISK)
CATALYTIC	EXCELLENT	EXTREME MODIFICATION (EXTREMELY HIGH DEVELOPMENT RISK)	EXTREME MODIFICATION (EXTREMELY HIGH DEVELOPMENT RISK)

*DEVELOPMENT RISK IS DEFINED AS THE ABILITY TO CONVERT A DEMONSTRATED EXPERIMENTAL TECHNIQUE INTO AN OPERATIONAL ENGINE COMBUSTOR.

TABLE III. - STRATOSPHERIC CRUISE EMISSION REDUCTION PROGRAM - PHASE I ELEMENTS

LEAN COMBUSTION	EFFECT OF CYCLE PRESSURE ON NO_X EFFECT OF VAPORIZATION EFFECT OF FLAMEHOLDER SHAPE AUGMENTATION TECHNIQUES
FUEL-AIR PREPARATION	INLET TURBULENCE CHARACTERIZATION EXTERNAL VAPORIZATION TECHNIQUES RADIAL MIXING CONTROL
AUTOIGNITION AND FLASHBACK	PARAMETRIC STUDY EFFECT OF HOT SURFACES EFFECT OF BOUNDARY LAYERS EFFECT OF ENGINE TRANSIENTS
ENGINE CONSTRAINTS	NONUNIFORM COMPRESSOR DISCHARGE ENGINE TRANSIENT CHARACTERIZATION NONIDEAL TURBINE INLET PROFILES

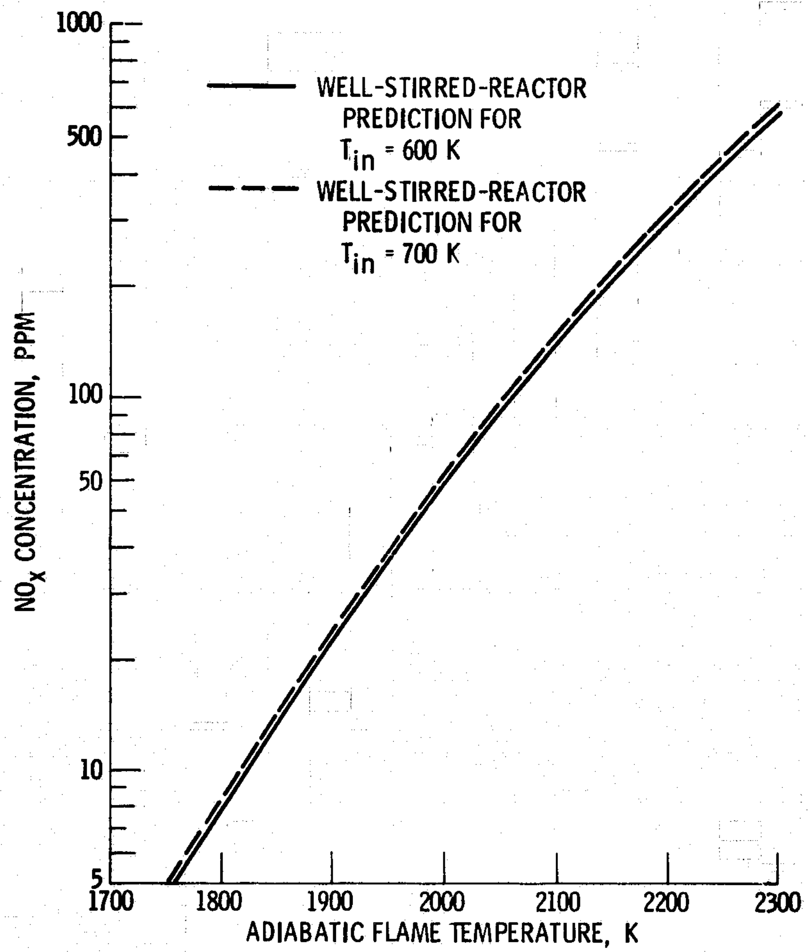


Figure 1. - Effect of flame temperature on the theoretical oxides of nitrogen concentration formed in a homogeneous prevaporized-premixed combustion process. Inlet pressure, 56 N/cm^2; residence time, 2 milliseconds.

E-8458

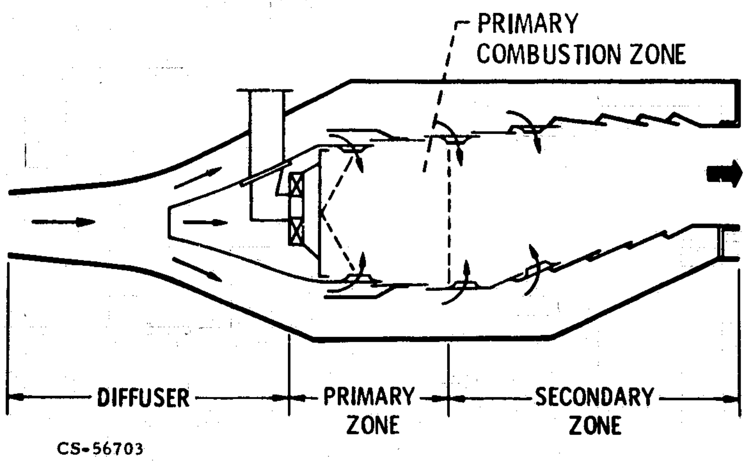


Figure 2. - Conventional annular combustor.

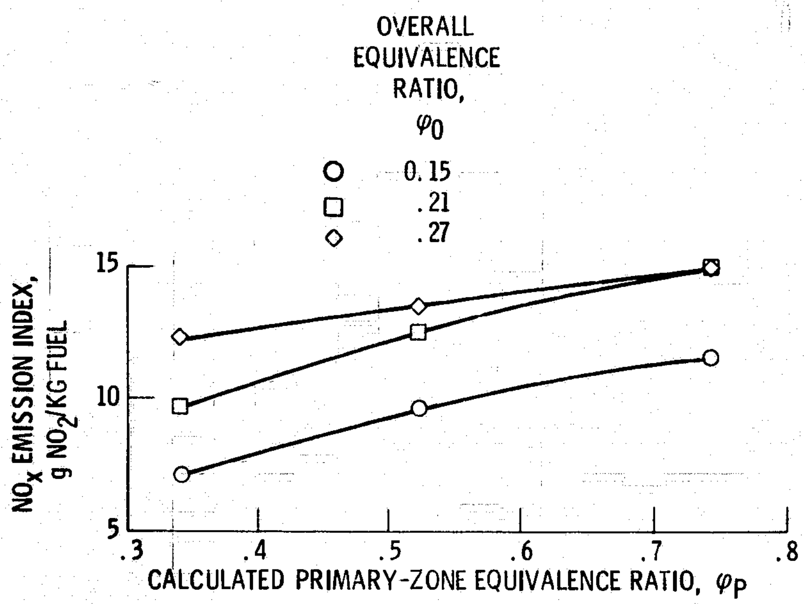
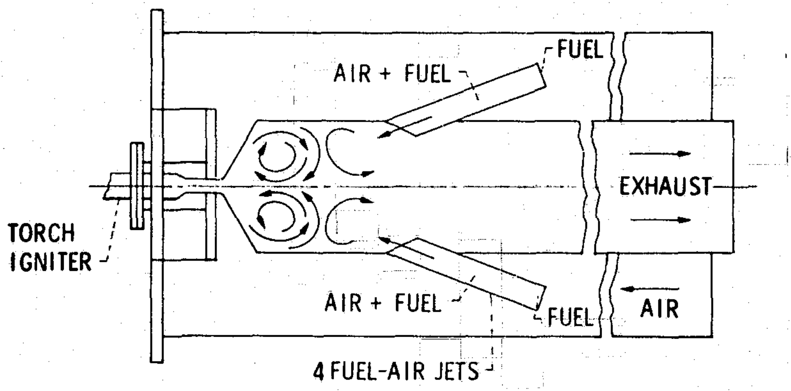
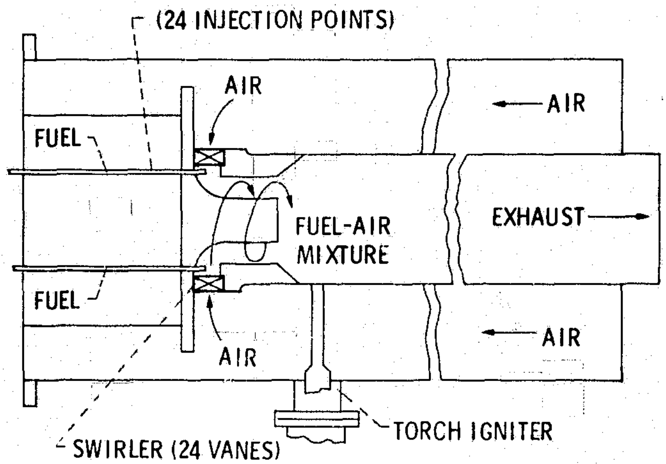


Figure 3. - Effect of primary-zone equivalence ratio on NO_x emissions for varying overall equivalence ratio in a "conventional" combustor. Jet A fuel; inlet temperature, 810 K; inlet pressure, 40 N/cm^2; reference velocity, 21.3 m/sec.



(a) JET-INDUCED COMBUSTOR CONCEPT.



(b) VORTEX AIRBLAST COMBUSTOR CONCEPT.

Figure 4. - Schematic illustration of advanced combustor concepts used in fundamental experiments at SOLAR.

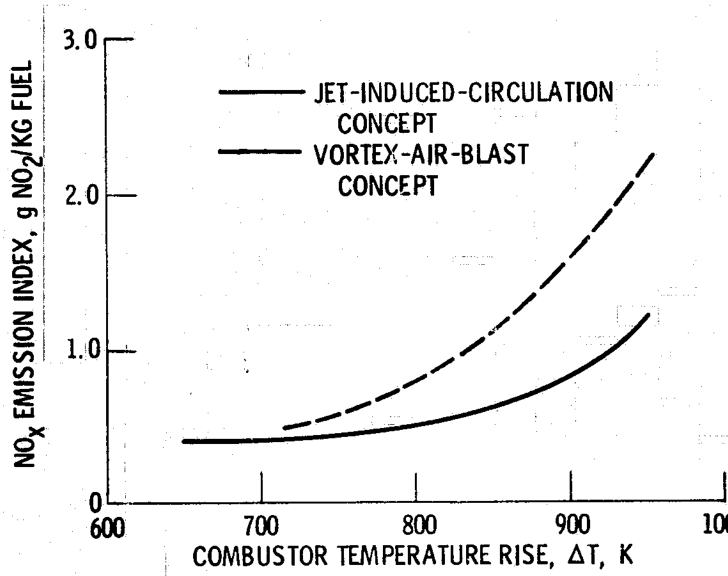
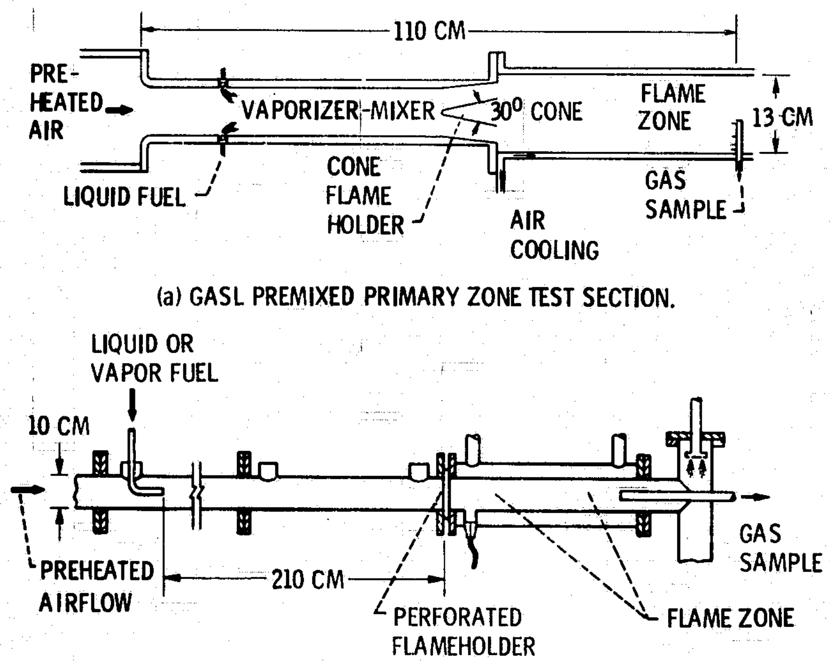


Figure 5. - Effect of combustor temperature rise on the NO_x emissions of two SOLAR low NO_x combustor concepts. Jet A-1 fuel. Inlet temperature, 830 K; inlet pressure, ~20 N/cm^2.



(a) GASL PREMIXED PRIMARY ZONE TEST SECTION.

(b) NASA PREMIXED PRIMARY ZONE TEST SECTION.

Figure 6. - Schematic illustration of the experimental "flame-tube" apparatus used in the GASL and NASA prevaporized-premixed combustion studies.

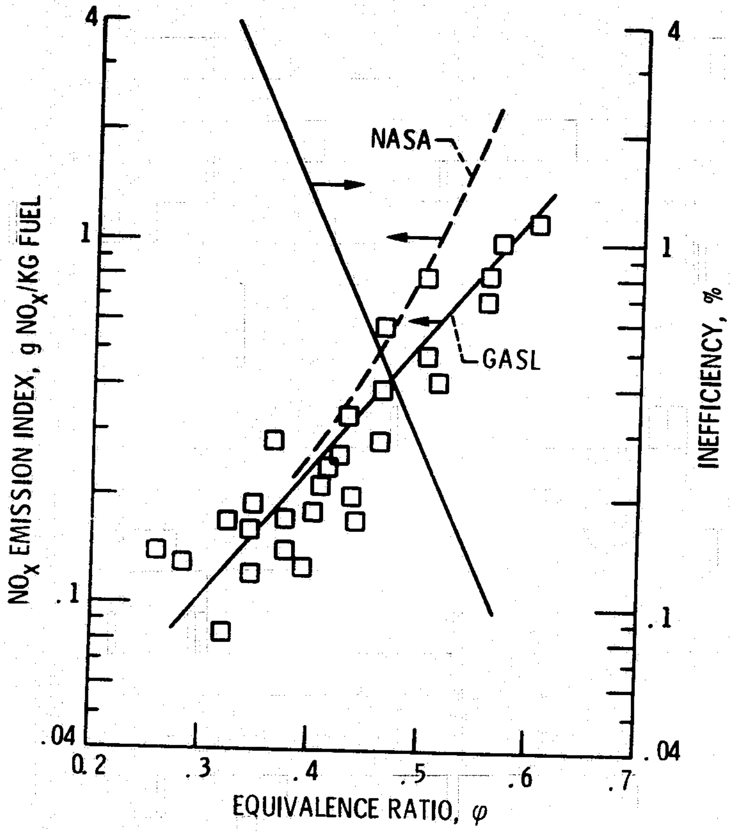


Figure 7. - Impact of combustion equivalence ratio on the formation rate of oxides of nitrogen and on combustion inefficiency for the GASL and NASA fundamental experiments. Inlet pressure, 40 N/cm^2; inlet temperature, 830 K; Jet A fuel.

CS-73160

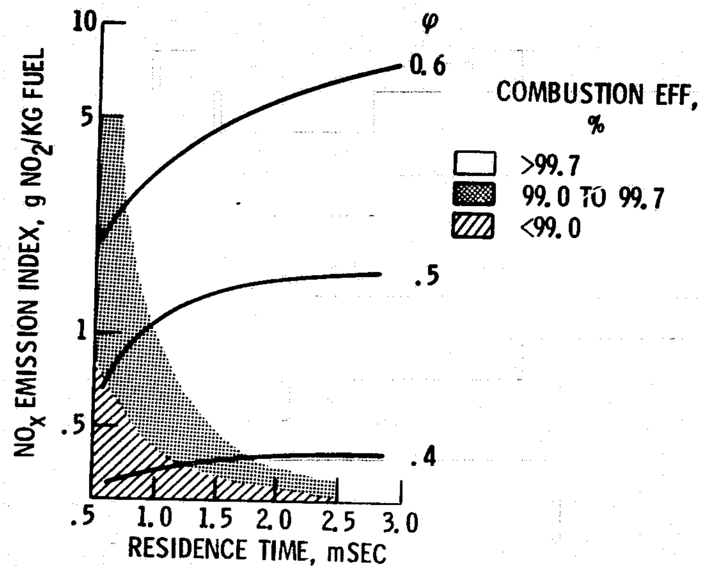
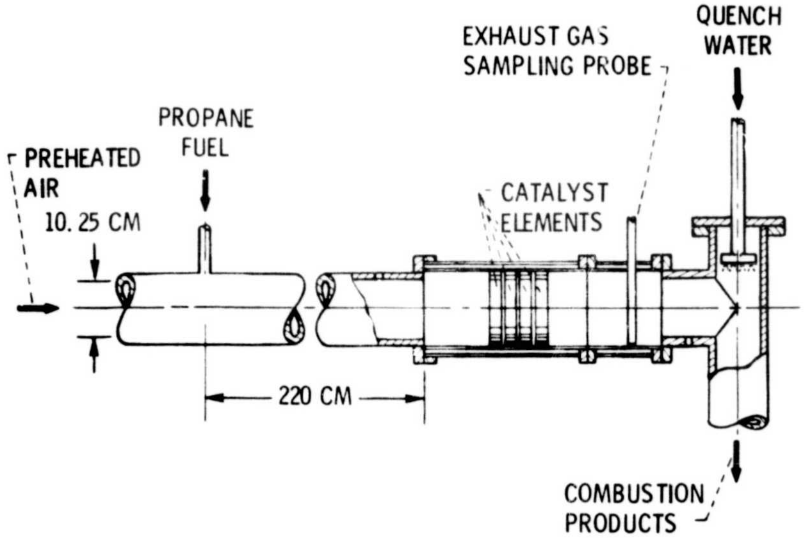
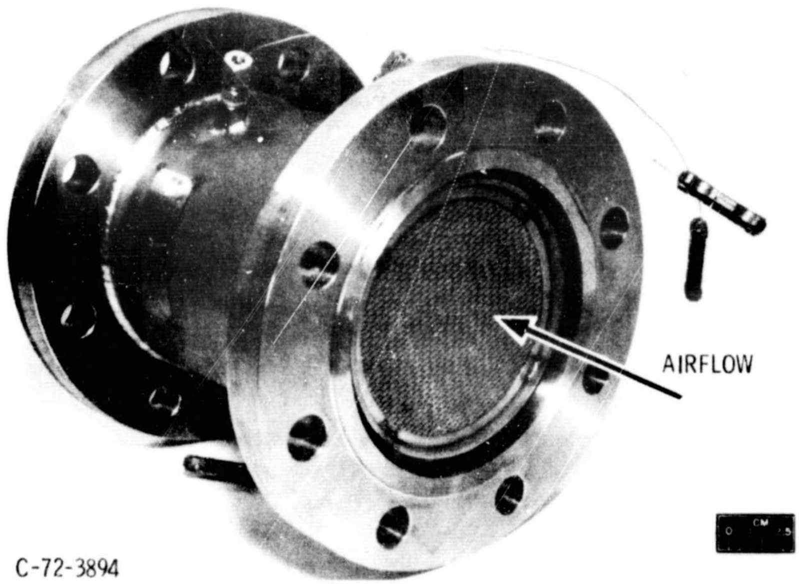


Figure 8. - Impact of combustion residence time and equivalence ratio on the formation of oxides of nitrogen and combustion efficiency in a prevaporized/premixed flame zone. Inlet pressure, 60 N/cm^2; inlet temperature, 700 K; gaseous propane fuel.



(a) TEST APPARATUS.



(b) CATALYTIC REACTOR.

Figure 9. - Schematic illustration of NASA catalyst element experimental test apparatus.

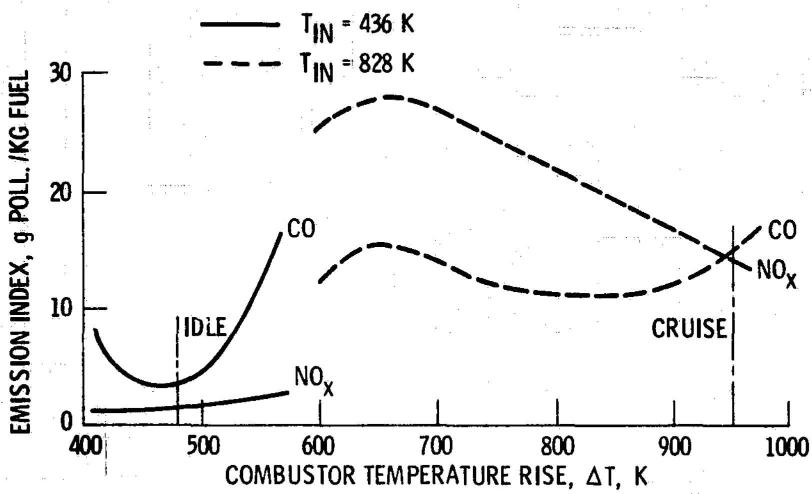
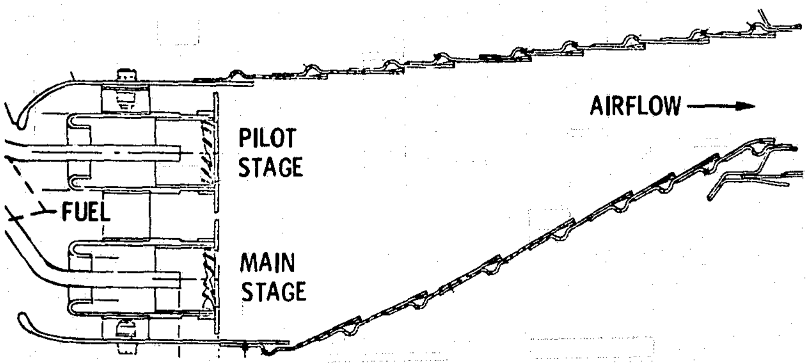
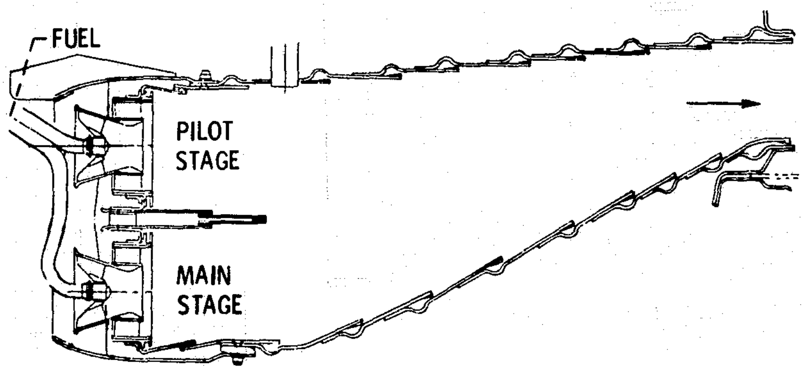


Figure 10. - Effect of an optimized idle equivalence-ratio on the cruise emissions of a fixed geometry configuration of the SOLAR VAB concept. Inlet pressure, 1.4 N/cm^2; Jet A-1 fuel.

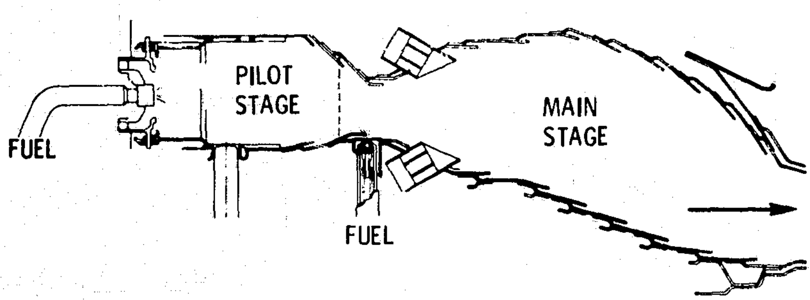
E-8552



(a) SWIRL-CAN MODULAR CONCEPT.



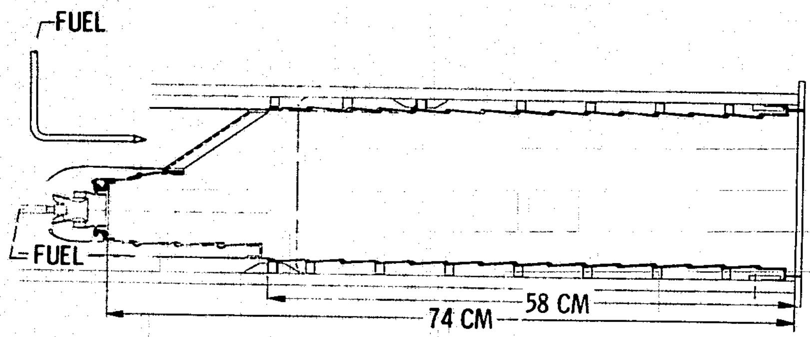
(b) DOUBLE-ANNULAR CONCEPT.



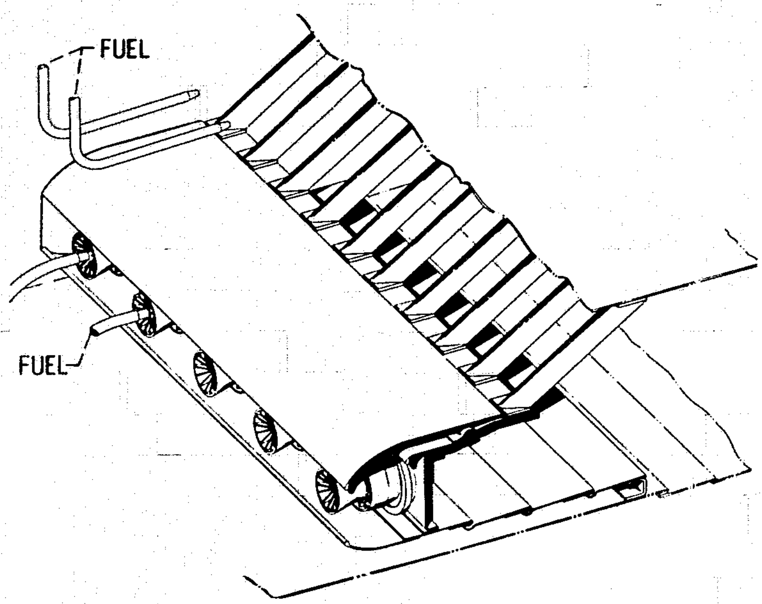
(c) VORBIX CONCEPT.

Figure 11. - Schematic illustration of the three types of advanced combustor concepts evaluated at simulated supersonic cruise conditions.

E-8858



(a) CROSS-SECTIONAL VIEW.



(b) CONFIGURATION SKETCH.

Figure 12. - Schematic illustration of staged-combustion advanced duct-burner concept for a supersonic cruise engine.

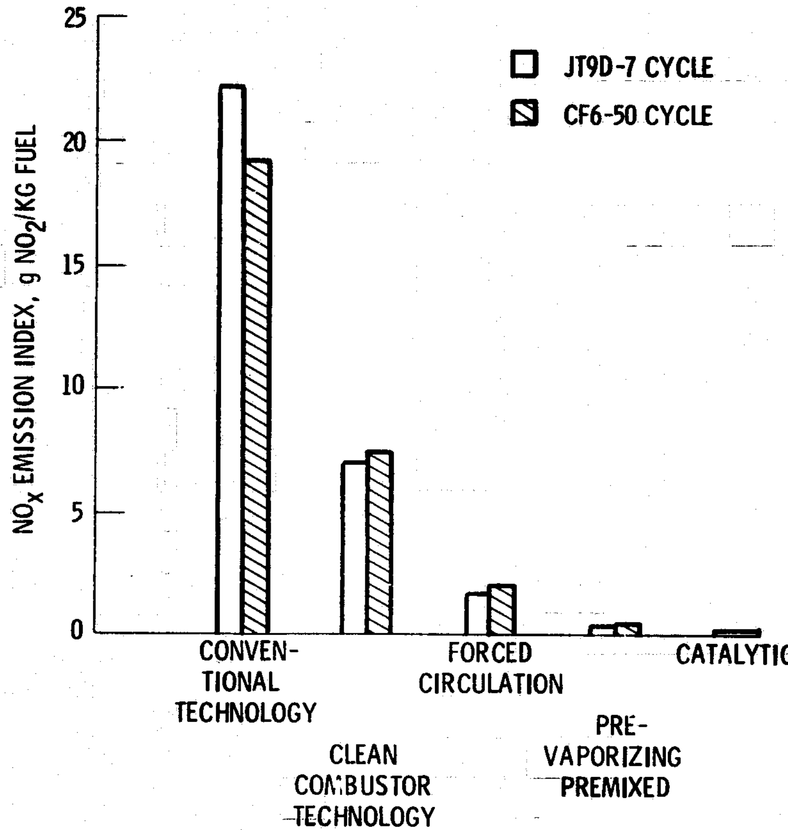


Figure 13. - NO_x emissions forecast for subsonic cruise, Mach number = 0.85 at 10.7 km altitude.

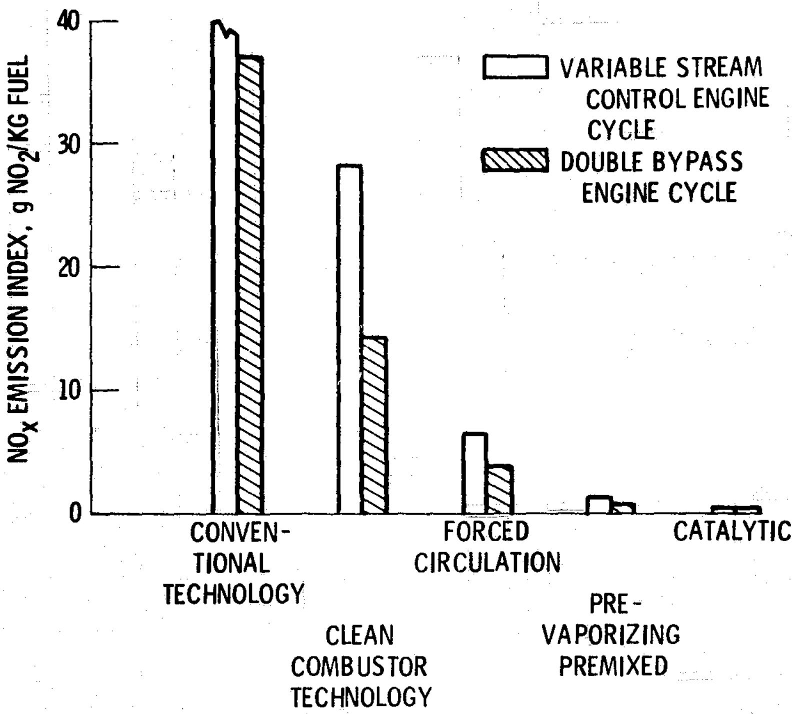


Figure 14. - NO_x emissions index forecast for supersonic cruise, Mach number = 2.32 at 16 km altitude.

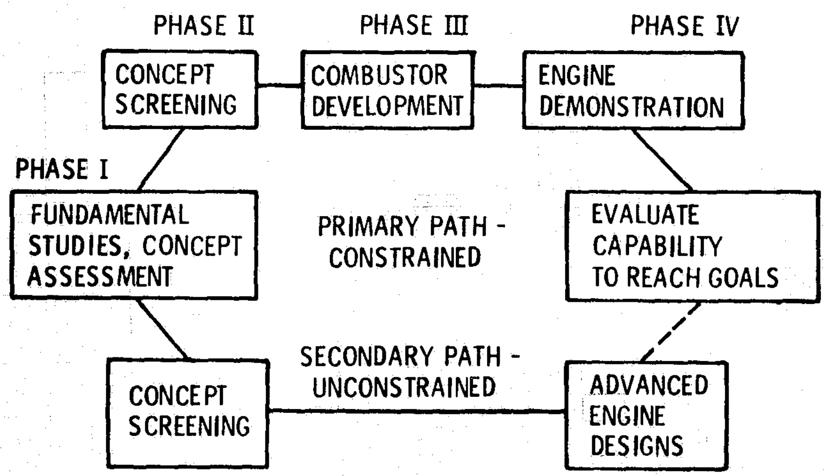


Figure 15. - Program phases for the Stratospheric Cruise Emission Reduction Program.

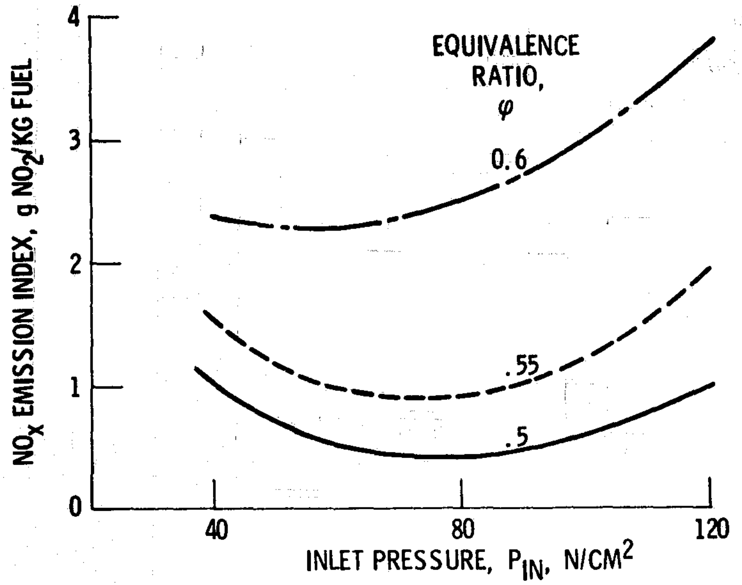


Figure 16. - Effect of inlet pressure and equivalence ratio on NO_x emissions from the GASL experiment. Inlet temperature, 900 K; Jet A fuel.

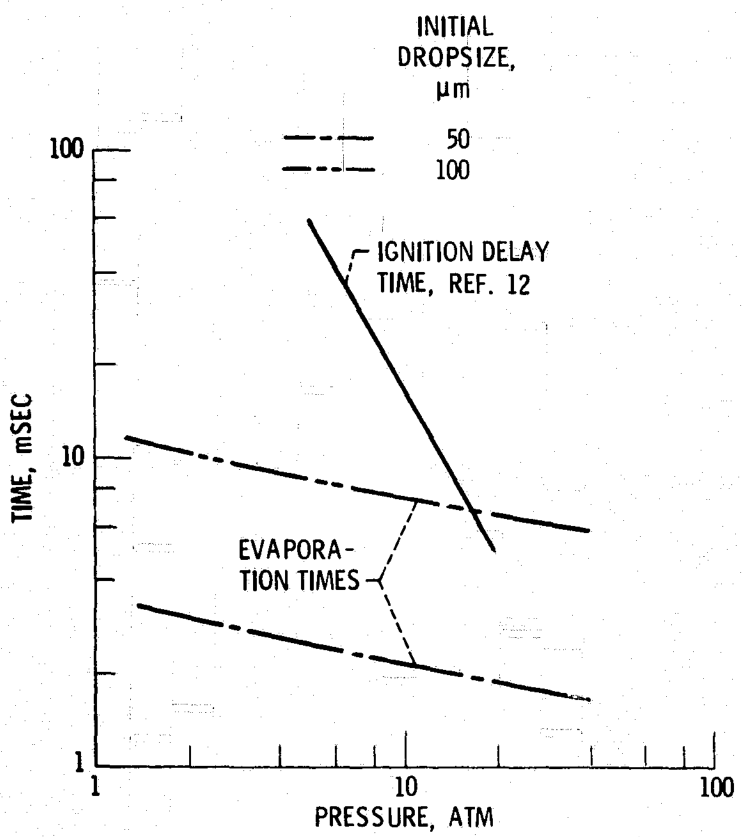


Figure 17. - Effect of pressure on ignition delay and vaporization times for JP-4. Inlet air temperature, 833 K.

E-8851